Magnetoelastic vibration damping properties of TbDy alloys

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ABSTRACT

Damping of axial and bending mode vibrations in giant magnetoelastic polycrystalline TbDy alloys was studied at cryogenic temperatures. All specimens of TbDy were arc-melted in the proper composition ratio and dropped into a chilled copper mold. Additional treatments consisted of cold plane-rolling to induce crystallographic texture and then heat-treating to relieve internal stress. Mechanical hysteretic losses were measured at various strains, frequencies, and loading configurations down to 77 K. Both as-cast and textured polycrystalline TbDy samples were tested along with an aluminum specimen for comparison. Loss factors at multiple natural vibration frequencies of the samples were measured for axial modes. Larger damping rates were measured for axial mode vibrations than for bending mode vibrations, possibly reflecting the larger specimen volume contributing to magnetoelastic damping. At LN_2 temperatures TbDy materials demonstrated $\eta > 0.05$ at 0.01 Hz and $\eta > 0.1$ at higher frequencies from 0.6–1.5 kHz.

1. INTRODUCTION

1.1 Background

Future NASA missions (e.g. TPF, SAFIR, LF) require larger optical apertures and must operate at cryogenic temperatures to achieve their science goals. As the size of the primary optic grows, it tends to be more flexible since total mass in orbit must remain within launch vehicle capabilities and is generally reduced at the expense of reduced stiffness. These space-based precision optical systems suffer from jitter due to both on-board and environmental disturbances that must typically be quieted with passive or active damping effective at low frequencies. However, if the telescopes must be cooled to a few degrees Kelvin, typical vibration damping materials such as viscoelastic materials, rheological fluids, viscous root dampers and many piezoelectric systems, become less effective—their loss mechanisms diminishing or freezing out of the system. The need for high vibration damping properties at low temperatures has led us to investigate the magnetomechanical properties of polycrystalline TbDy alloys as candidate materials.

Ferromagnetic TbDy alloys exhibit giant magnetostriction, a large coupling between strain and magnetization, when cooled below the Curie temperature, T_C, approaching 1% at 4 K. Specifically, as TbDy alloys are strained in either tension or compression along a direction that lies in the easy plane of magnetization, the alloy's magnetic domains in the material reorient so as to produce a magnetization perpendicular to the direction of strain. Where magnetization proceeds largely by domain wall motion, these processes are subject to hysteretic losses and result in mechanical damping. Because TbDy alloys maintain this magnetoelastic damping property at all temperatures below T_C, they are immune from the performance degradation problems at cryogenic temperatures exhibited by other candidate materials for passive damping.

The magnitude of the damping loss factor depends strongly on the magnetomechanical coupling factor describing the efficiency of converting elastic to magnetic energy, the magnetic anisotropy describing the difficulty of moment rotation, the Young's modulus, the magnetization, the magnetostriction and the crystallographic texture.[1] These properties and hence the damping characteristics of the material can be optimized through control of composition and microstructure. The magnetic and magnetoelastic properties of these alloys vary with the composition ratio, for example, T_C = 188 K for $Tb_{0.76}Dy_{0.24}$ while for $Tb_{0.6}Dy_{0.4}$, T_C = 165 K. The two composition ratios, $Tb_{0.76}Dy_{0.24}$ and $Tb_{0.6}Dy_{0.4}$ are commonly chosen because the magnetic anisotropy is minimized for 4 K and 77 K, respectively. We expect the damping of optimized polycrystalline TbDy to be substantial based on its large magnetostriction, magnetomechanical coupling factors as high as 0.75,[2] and the relatively large hysteresis measured in curves of magnetostriction versus applied field.[3-5]

While the largest magnetostrictions occur for single crystal TbDy alloys, our investigation focuses on polycrystalline TbDy damping properties for several reasons. First, single crystals are difficult and expensive to produce in the case of TbDy alloys, while polycrystalline alloys can be produced more easily using common metallurgical processing techniques. Second, the interaction between grain boundaries, misoriented grains and internal stresses with magnetoelastic damping mechanisms in polycrystalline TbDy alloys is complex, but has the potential to enhance damping properties. Domain wall motions are impeded when they encounter inclusions, dislocations, impurities such as the Ta, N, and O commonly found in rare earth material, and micro-stresses, all of which may be increased by switching to polycrystalline materials.

Other factors which are known to affect material damping include temperature, frequency, configuration, strain sense, strain amplitude, and environmental effects. In the case of laminated composite materials, fiber volume ratio, layup orientation, and internal damage from past loading events also play a role. This complicates the comparison between different tests and makes it difficult to extrapolate to other situations. For b.c.c. and f.c.c. metals, Zener theory predicts the thermoelastic energy loss in beams undergoing cyclic bending strains. Dependence on temperature, frequency, and beam thickness are captured in the theory; however, the theory does not apply for axial and torsional strains, for materials other than b.c.c. and f.c.c. metals, or for configurations other than rectangular beams. Many room temperature damping measurements have been made to validate the Zener theory, with much success.

1.2 Previous experiments

In previous work with polycrystalline TbDy, we measured quasi-static magnetomechanical energy dissipation as the ratio of the area of the stress-strain hysteresis loop to the mean area under the loading and unloading curves, $\Delta E/E$.[6] An example curve is shown in Fig. 1. The energy lost is the product of the fractional dissipation with the total potential energy stored in the sample. These previous experiments measuring the damping of compressive stresses of polycrystalline TbDy alloys at low frequencies (~0.1 Hz) demonstrate large damping capacities up to 36% per cycle at 77 K of loads of tens of GPa applied in an axial direction, corresponding to a loss factor of η = 0.057. The damping of mechanical energy in these experiments was determined by measuring the area of a stress-strain hysteresis loop over a cycle of compressive strain as stress-strain curves at both room temperature and 77 K temperatures, with room temperature damping negligible. These results are summarized in Table 1.[7]

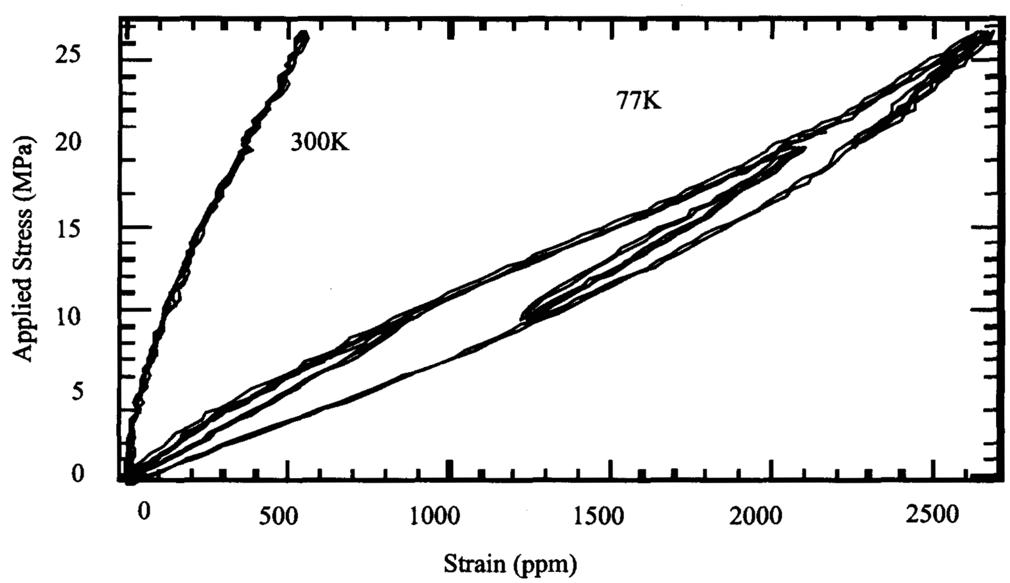

Fig. 1: Quasistatic stress-strain curves of polycrystalline $Tb_{.76}Dy_{.24}$, 99.7% commercial grade purity, showing major and minor loops at 77 K. Above 25 MPa, the hysteresis decreases substantially, indicating saturation of the stress-induced magnetic domain alignment. The figure shows such a hysteresis loop measured at 77 K. Two minor loops are centered about strains of 450 and 1675 ppm and clearly show an increase in the effective elastic modulus. A room temperature stress-strain curve without hysteresis is also shown.

These results indicate the potential viability of TbDy as an effective cryogenic damping material at the low frequencies and lower strains experienced during vibration damping applications. Within the studied range, maximum damping was measured at smaller strains, indicating changes in magnetization processes at higher strains. The commercial purity $Tb_{.76}Dy_{.24}$ textured alloy showed 30% higher damping for the 0-900 ppm range at 77 K than the high purity alloy. The implication is that the additional impurities in the commercial grade specimens act as additional pinning sites for domain walls, however the matter is complicated by the additional effect of impurities on texture.[7]

Sample	Strain Range	Loss factor $\eta = \psi/2\pi$
$Tb_{.76}Dy_{.24}$, textured polycrystalline, 99.7% purity	0 to 2700 ppm	0.031
	0 to 900 ppm	0.036
	0 to 600 ppm	0.050
	1250 to 2100 ppm	0.026
	170 to 270 ppm	0.057
$Tb_{.76}Dy_{.24}$, textured polycrystalline 99.94% purity	0 to 2150 ppm	0.022
	0 to 900 ppm	0.027
	1100 to 1750 ppm	0.021

Tbl. 1: Quasistatic damping loss factors at various stress ranges for commercial and 99.94% high purity grade textured polycrystalline $Tb_{.76}Dy_{.24}$ over various strain ranges.

2. MATERIAL PREPARATION

For production of polycrystals, the TbDy alloy is arc melted in the proper composition ratio and dropped into a chilled cylindrical mold, creating an ingot about 1" in diameter and several inches long. Specimens were prepared from commercial grade TbDy with a typical purity of 99.7%, with the main impurities being Ta, O, and N, and from high purity 99.94% TbDy. The as-cast ingot shows strong radial texture, with grain growth inward from the edges of the ingot. For purposes of magnetoelastic coupling of TbDy, the ideal case of a single crystal is best approximated by a polycrystalline alloy with grains oriented such that their hexagonal basal planes are close to parallel. Therefore, changing the texture of the as-cast samples through plastic deformation is necessary to improve magnetoelastic coupling properties of TbDy alloys. The effect of texture on damping properties is critical and complex due to the elastic interactions of misaligned grains of TbDy alloys and the large anisotropy of the material.

The first step in the texturing of polycrystalline TbDy samples is a deformation by plane rolling of 35% reduction in thickness, followed by a heat treatment at 950°C to induce recrystallization. The deformation randomizes the grain orientations, while the annealing at high temperature (approximately 500°C below the melting point) allows for further grain growth as well as strain relief. The net result is a sample suitable for more specific deformation. A second set of plane-rolling deformations was then performed with the intent of reorienting the grains in a particular common direction. Because TbDy alloys have a hexagonal crystal structure, the c-axes of the grains align parallel to the direction of applied stress. This can be seen in optical micrographs, with the slip lines as faint lines of contrast within a grain of TbDy. Each sample was then annealed for strain relief.

3. EXPERIMENTAL PROCEDURE

Higher frequency magnetoelastic damping properties of TbDy samples were tested by measuring the damping of bending mode vibrations of a rectangular sample using the apparatus shown in Fig. 2. Each sample is clamped to a copper base and a stainless steel block is clamped to the top of the sample. Stainless steel was chosen for the clamp due to its non-magnetic properties and relatively large density, which allowed for a large mounted mass atop each sample and the corresponding lower frequencies of vibration. The clamps were designed so that they tighten when cooled. On this stainless block is a cryogenic piezoelectric accelerometer used to measure the motion of the top of the sample. Thin gauge wire was used as the leads for the accelerometer in order to minimize interference with the vibrating sample. A second accelerometer measured the vibrations of the copper mounting block. The stainless block was struck by a steel or plastic ball bearing released via solenoid actuation from a tube aimed at the face of the block opposite of the accelerometer.

Samples of 6061 Aluminum were tested in the bending configuration as a control. By comparing the Al measurements with Zener predictions at room temperature, it can be verified that the parasitic damping sources in the apparatus have been eliminated. Moreover, the use of Al samples as similar as possible to the TbDy samples provided a meaningful comparison of damping loss factors in both bending and axial mode tests.

The apparatus is encased in a vacuum bell jar and cooled with liquid nitrogen (LN_2) from 300 K to 80 K, with measurements made at temperatures on both sides of the sample's Curie point. A cooled copper box enclosed the specimen and measurement apparatus in order to shield them from radiation sources. Tests were conducted at pressures of 10^{-3}–10^{-6} Torr. Vibration acceleration data was collected through a National Instruments data acquisition card at 10–25 kHz and processed in order to determine the natural bending mode frequencies. Each data set was filtered with a Butterworth bandpass filter centered at the most prominent low frequency mode as determined by Fourier analysis. The lowest primary frequencies of bending mode vibration ranged from 70–350 Hz depending on sample composition, dimensions and temperature. The bandpass filter width was set at ±5–40 Hz, with proportionally larger bandpass windows used at higher frequencies.

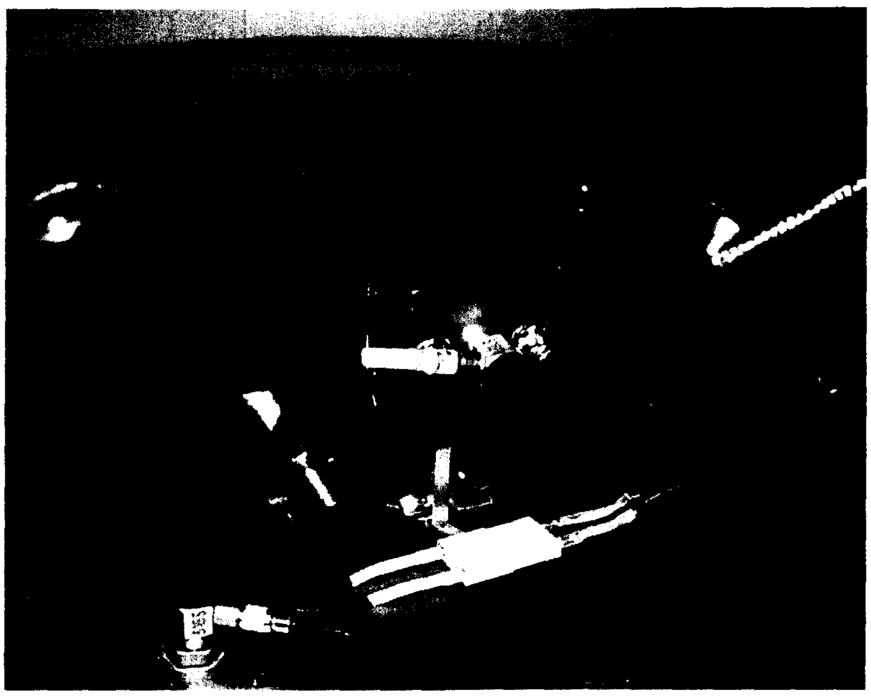

Fig. 2: Experimental apparatus showing a 6061cast aluminum sample clamped to the copper base. Accelerometers are mounted on the stainless steel block clamped to a cast aluminum sample and the copper base.

Damping loss factor was then calculated for the filtered signals and analyzed as a function of time, maximum strain, and sample temperature. The mean logarithmic decrement, $\delta = \ln (A_n/A_{n+1})$ is often used to describe the damping capacity of materials, with A_n corresponding to the vibrational amplitude of the n^{th} oscillation of a vibrating element. The damping of the peak amplitude of the sample signal was computed first by determining local maxima of the accelerometer signal. By fitting the peaks of the 75 oscillations to decaying exponential curves, we can determine δ. This quantity was converted to loss factor defined in Equation 1.

$$\eta = \delta/\pi = (1/m\pi) \ln (A_n/A_{n+m}). \quad (1)$$

For this calculation, accelerometer signal data was converted into accelerometer displacement through double integration, and the maximum strain in the sample was computed from accelerometer displacement using the Equation 2.

$$\varepsilon = 3\Delta Y/L^2. \tag{2}$$

Here, Δ is the displacement of the accelerometer, Y is 1/2 the thickness of the beam and L is the distance between the base clamp and the accelerometer, the effective specimen length. This equation provides a general result of maximum bending strain assuming uniform bending of the sample above the base clamp. The bending strain decreases closer to the accelerometer (i.e. the top of the sample) and closer to the neutral beam axis, further from the sample's back and front edges.

According to simple Euler-Bernoulli bending theory for prismatic beams, only a fraction of the sample's volume can be found to experience appreciable amounts of strain. The volume fraction of a sample in this configuration experiencing between fractions α and β of the calculated maximum strain during bending mode vibrations is expressed in Equation 3.

$$V_{pct} = \beta - \alpha + \alpha\ln\alpha - \beta\ln\beta. \tag{3}$$

To find the percent volume of a beam with between 50% and 100% maximum strain, for example, we can calculate:

$$V_{pct} = 1 - 0.5 - 0.347 = 15.3\%. \tag{4}$$

Because the magnetoelastic properties of a sample of TbDy rely on strain-induced magnetization, we may speculate that the diminished strains experienced by much of a sample's volume during bending mode vibrations will limit damping performance.

A second set of experiments was carried out to determine axial mode damping of aluminum and TbDy samples. The bending mode damping measurement apparatus was modified to accommodate impact from above. In this experiment, a solenoid-driven rod provided the source of vibration and the stainless steel clamp was modified to allow for impact on a flat surface. The accelerometers were moved to measure axial vibrations on the copper block and stainless steel clamp normal to the direction of impact. Strain induced by a particular axial mode of vibration is computed by integrating the accelerometer signal to obtain displacement and then dividing by the length of the sample. The total strain experienced throughout the sample's volume may be calculated by summing over the primary modes of vibration. An exponential curve is then fit to the peaks of the oscillations for each test and the loss factor resulting from the axial mode damping is calculated. Owing to the few high amplitude peaks available in a time series of heavily damped axial mode free vibrations, this approach proved preferable to calculating damping as a function of strain for each test. We compared the calculated loss factors with peak strain from 300 K to 80 K and at two sets of frequencies to determine the effects strain, frequency, and temperature variations on the magnetoelastic damping properties of our samples.

4. RESULTS AND DISCUSSION

4.1 Bending mode vibration damping

Previous aluminum damping measurements indicate aluminum exhibits $\eta < 0.001$ and amplitude independent behavior below 100 K in the relevant range of frequency and strain. In order to establish the effects of the experimental apparatus on bending mode damping measurements, the damping properties of a cast aluminum sample, measuring 3x2x40mm, were investigated at various temperatures, from 300 K to 80 K.

The accelerometer data was bandpass filtered ±5 Hz around natural frequencies of 75 Hz, 77 Hz and 79 Hz at 300 K, 223 K and 123 K, respectively. We calculated the strain using Eq. 2 to produce plots of loss factor verses strain, as shown in Fig. 3. Each measurement of bending mode damping in aluminum showed the predicted and previously observed amplitude independent behavior. At 300 K the Zener theory predicts loss factor of 1.4×10^{-3} for the specimen measured here. The theory underpredicts the measured value of 1.8×10^{-3} by only about 30%, which is likely attributable to the use of handbook values for the physical properties in the calculations. The close agreement between calculated and measured damping verifies that the parasitic damping sources in the apparatus have been eliminated.

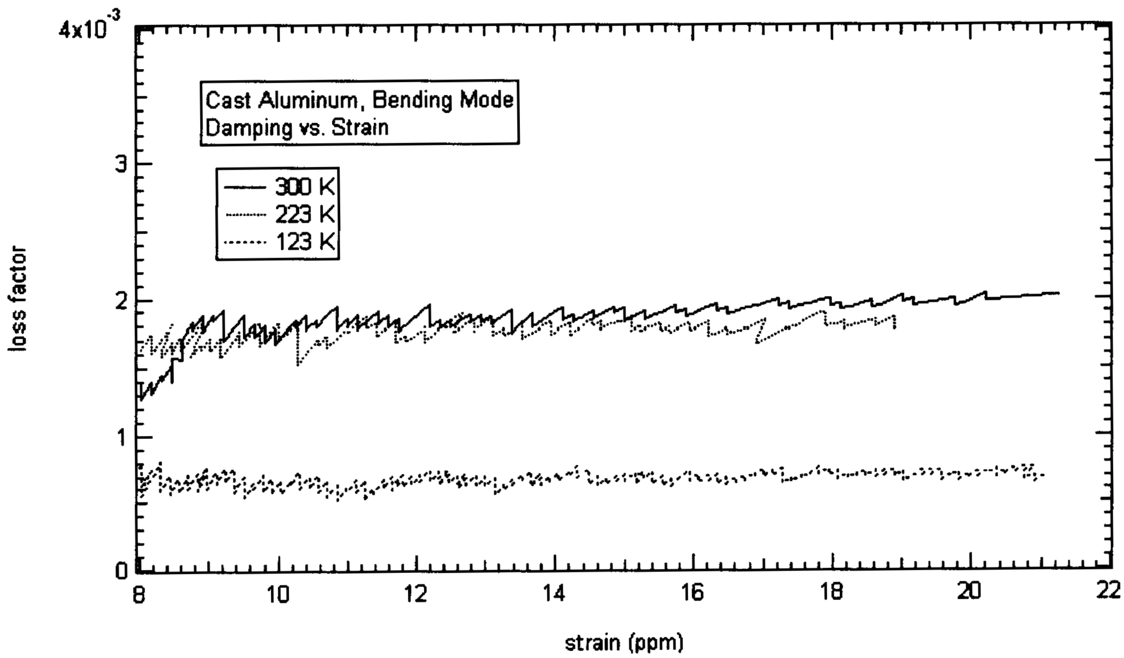

Fig. 3: Bending mode damping of 6061 cast aluminum for 300K, 223K, and 123K.

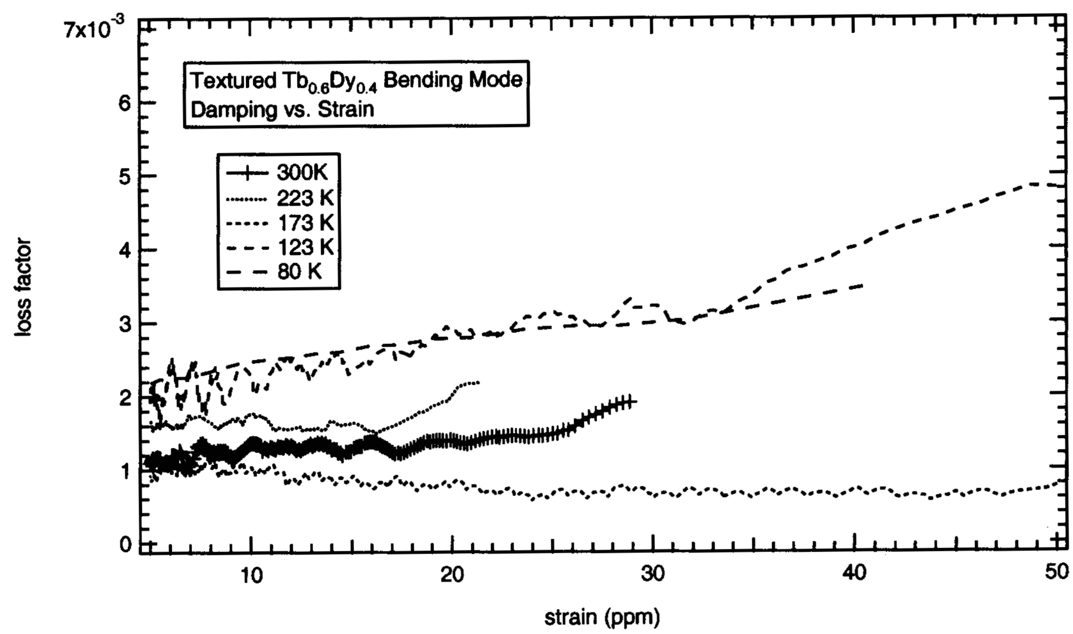

Fig. 4: Loss factor versus peak strain for polycrystalline TbDy bending mode vibrations at various temperatures.

A series of similar tests was performed on a sample of commercial grade, textured $Tb_{0.6}Dy_{0.4}$. The results can be seen in Fig. 4. Several observations can be made regarding this data. First, the results do not conform to the Zener theory of amplitude independent damping. This is not surprising given that this theory is not intended to describe magnetoelastic mechanisms of loss. Second, damping is smaller above the Curie temperature of 165 K, and lowest at the coldest temperature above T_C measured, 173 K. Below T_C, damping is larger, and increases noticeably at higher strain amplitudes. The damping measured at temperatures below T_C approaches three times the largest measured damping above the Curie point. This is significant given the possibility that only a small volume of the bulk specimen contributes strain-induced magnetoelastic losses and suggests the potential for thin coatings to be effective contributors to system damping.

4.2 Axial Mode Vibration Damping

Damping of axial mode vibrations were measured for four samples: a 6061 cast aluminum control sample, an as-cast, untextured $Tb_{0.6}Dy_{0.4}$ polycrystalline sample, a similarly prepared untextured $Tb_{0.76}Dy_{0.24}$ polycrystalline sample and a textured $Tb_{0.6}Dy_{0.4}$ polycrystalline sample of identical composition, referred to as cast aluminum, as-cast $Tb_{0.6}Dy_{0.4}$, as-cast $Tb_{0.76}Dy_{0.24}$, and textured $Tb_{0.6}Dy_{0.4}$, respectively, for the remainder of the discussion. Fourier analysis of the resulting accelerometer data revealed the existence of multiple modes of vibration, with the lowest two natural frequency modes the primary contributors to sample strain. In the case of the control sample of cast aluminum, modest decreases in damping were observed for cold temperatures versus room temperature, with room temperature results before and after cooling consistent. This suggests that the effects on damping caused by thermal expansion of the apparatus are negligible. The decrease in damping with temperature observed in axial stress is consistent with the trend of the cast aluminum samples subjected to bending.

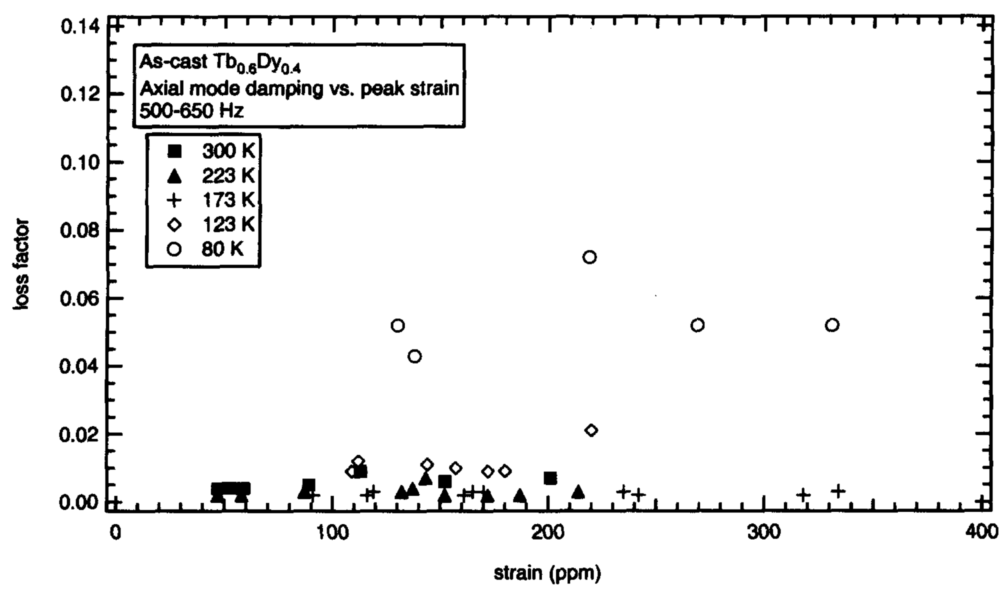

Fig. 5: Effects of temperature on axial mode damping of as-cast $Tb_{0.6}Dy_{0.4}$.

For the as-cast $Tb_{0.6}Dy_{0.4}$ sample, damping increases markedly for the primary axial mode vibration below the Curie temperature of 165 K, as shown in Fig. 5. This is consistent with damping magnitudes evident in quasi-static tests.[6,7] Further, the peak strains experienced by the sample in this mode of vibration are significantly larger than the strains experienced by most of the volume of the sample used during bending mode tests. The damping is largely independent of strain amplitude in the range measured, from 50-350 ppm. The magnitude of the loss factor at 80 K averaged 0.054 for this range of strain, which compares well to measured quasi-static damping. As-cast $Tb_{0.76}Dy_{0.24}$ shows similar behavior as seen in Fig. 6, however a marked amplitude dependence is seen and the loss factor is even higher at all measured temperatures.

An important difference between the damping characteristics of the as-cast $Tb_{0.76}Dy_{0.24}$ sample and the as-cast $Tb_{0.6}Dy_{0.4}$ sample can be seen by comparing the first and second mode loss factors at 300 K and 80 K, as listed in Tbl. 2. As-cast $Tb_{0.76}Dy_{0.24}$ exhibits the expected frequency independent behavior, while $Tb_{0.6}Dy_{0.4}$ shows strong frequency dependence. It is possible that these differences arise from magnetic anisotropy differences between the specimens, and there is some supporting evidence given below. The magnetic anisotropy is considerably larger in the case of the $Tb_{0.76}Dy_{0.24}$, and has a strong effect on the mechanisms by which magnetization proceeds. This would not explain the differences in the first mode damping at 300 K however, which imply a difference in the microstructure or residual stresses. Further specimen tests are necessary to confirm and determine the cause of this behavior.

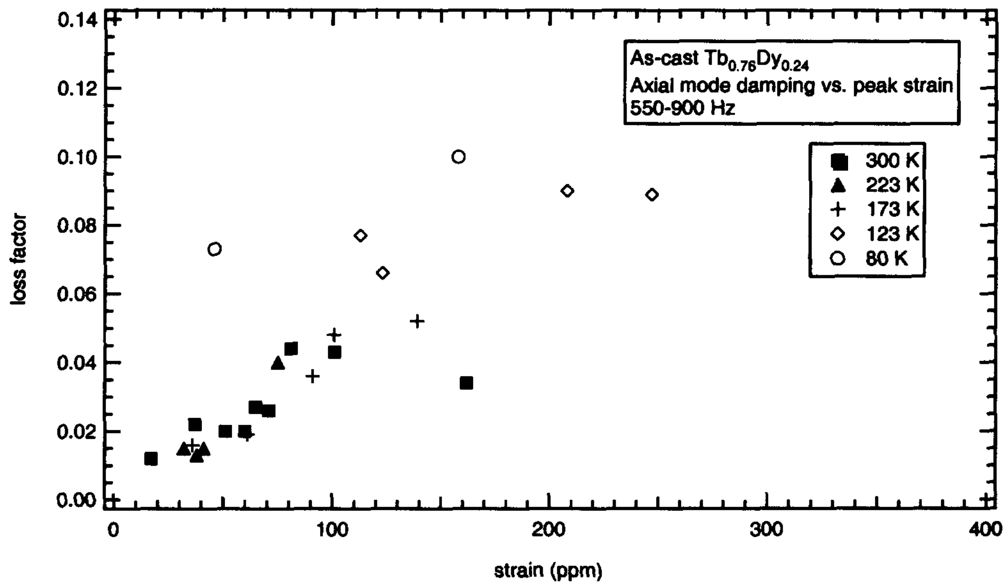

Fig. 6: Effects of temperature on axial mode damping of as-cast $Tb_{0.76}Dy_{0.24}$.

Sample	Average Damping Measured at 300K	Average Damping Measured at 80K
$Tb_{0.6}Dy_{0.4}$ as-cast polycrystalline alloy, 99.7% purity	η=0.023 at 2000 Hz	η=0.110 at 1250-1300 Hz
	η=0.005 at 650 Hz	η=0.054 at 500-550 Hz
$Tb_{0.76}Dy_{0.24}$ as-cast polycrystalline alloy, 99.94% purity	η=0.029 at 2200 Hz	η=0.099 at 1400-1450 Hz
	η=0.028 at 875 Hz	η=0.112 at 580-600 Hz
6061 cast aluminum	η=0.0013 at 1550 Hz	η=0.0009 at 1620 Hz

Tbl. 2: Effects of temperature on axial mode damping loss factors of as-cast TbDy alloy and cast aluminum samples.

Because of the varying elemental compositions of two of the TbDy samples and the resulting differences in Curie points, it was possible to study the effects of different magnetic properties on otherwise similar samples. An important difference between the damping characteristics of the as-cast $Tb_{0.76}Dy_{0.24}$ sample and the as-cast $Tb_{0.6}Dy_{0.4}$ sample can be seen by comparing 173 K second mode loss factors as listed in Tbl. 3. The $Tb_{0.76}Dy_{0.24}$ sample exhibits high damping and a reduced natural frequency at 173 K, similar to that at lower temperatures down to 80 K, unlike the low damping and increased natural frequency of the $Tb_{0.6}Dy_{0.4}$ sample. The fact that the Curie point of $Tb_{0.76}Dy_{0.24}$ is 188 K allows for magnetoelastic loss mechanisms at 173 K, and accounts for the increased damping of axial mode vibrations exhibited by this sample.

The textured $Tb_{0.6}Dy_{0.4}$ sample used in the previous bending mode damping tests was measured. Although this sample demonstrates higher damping below the Curie point of 165 K, results of axial mode tests were inconsistent, possibly due micro-cracking and other defects incurred during processing or repeated thermal and mechanical cycling series of testing. This is supported by the somewhat higher damping observed at temperatures above T_C for this sample relative to the as-cast $Tb_{0.6}Dy_{0.4}$.

Sample	Damping at 300K	Damping at 173 K	Damping at 80K
$Tb_{0.6}Dy_{0.4}$ as-cast polycrystalline alloy, Curie point = 165 K, 99.7% purity	η=0.023 at 2000 Hz	η=0.021 at 2050 Hz	η=0.110 at 1275 Hz
$Tb_{0.76}Dy_{0.24}$ as-cast polycrystalline alloy, Curie point = 188 K, 99.94% purity	η=0.029 at 2200 Hz	η=0.044 at 2050 Hz	η=0.099 at 1425 Hz
6061 cast aluminum	η=0.0013 at 1550 Hz	η=0.0009 at 1610 Hz	η=0.0009 at 1620 Hz

Tbl. 3: Loss factor, η, for the second natural frequency at 300 K, 173 K and 80 K. Note that for $Tb_{0.76}Dy_{0.24}$ at 173 K, the damping has increased and the natural frequency has decreased, as expected for the material at temperatures below the Curie temperature. Note in contrast that $Tb_{0.60}Dy_{0.40}$ shows a decreased loss factor and an increased natural frequency, as expected for the material at temperatures above the Curie temperature.

The very high damping of TbDy makes measurement through axial mode decay less exact than through bending mode due to the very small number of oscillations occurring before the vibration is damped out. These preliminary results indicate a preferable measurement approach is to excite a particular frequency and measure the phase angle, allowing more direct determination of the frequency and amplitude dependence for these high damping materials.

5. CONCLUSIONS

Damping of axial and bending mode vibrations in polycrystalline TbDy alloys, and in 6061 Aluminum specimens for comparison, was studied from 80–300 K. Higher damping was measured for axial mode vibrations than for bending mode vibrations, possibly indicating a larger specimen volume contributes to magnetoelastic damping. Bending mode measurements on TbDy demonstrated increasing damping with decreasing temperature below the Curie temperature and strain amplitude dependent behavior, as expected for magnetoelastic loss mechanisms. At LN_2 temperatures TbDy materials demonstrated $\eta > 0.1$ at frequencies from 0.6–1.5 kHz, and close agreement is seen with the quasi-static results indicating that the behavior may indeed by frequency independent over a wide range. In addition, the TbDy specimen natural frequencies clearly show the softening of the modulus once the material is cooled below the Curie temperature. By comparing the 6061 cast aluminum bending measurements with Zener predictions at room temperature, the parasitic damping sources of the apparatus were bounded. Moreover, the cast aluminum samples, as similar as possible to the TbDy samples, clearly showed much smaller damping loss factors at cryogenic temperatures. The high damping losses of TbDy at low temperatures demonstrate the potential use of this material in cryogenic vibration damping applications.

6. ACKNOWLEDGEMENTS

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